NeoBiota 32: 89–105 (2017)
doi: 10.3897/neobiota.32.9842
http://neobiota.pensoft.net

RESEARCH ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

Quantifying errors and omissions in alien species lists: The introduction status of *Melaleuca* species in South Africa as a case study

Llewellyn E.O. Jacobs[1,2,3], David M. Richardson[3], Brendan J. Lepschi[4], John R.U. Wilson[2,3]

1 *Scientific Services, CapeNature, Private Bag X5014, Stellenbosch 7599, South Africa* **2** *Invasive Species Programme, South African National Biodiversity Institute, Kirstenbosch Research Centre, Private Bag x7, Claremont, South Africa 7735* **3** *Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Matieland, South Africa 7602* **4** *Australian National Herbarium, Centre for Australian National Biodiversity Research, GPO Box 1700, Canberra, ACT 2601, Australia*

Corresponding author: *Llewellyn E.O. Jacobs* (llewellyn.jacobs@gmail.com; invasivespecies@sanbi.org.za)

Academic editor: *I. Kowarik* | Received 23 July 2016 | Accepted 19 October 2016 | Published 4 January 2017

Citation: Jacobs LEO, Richardson DM, Lepschi BJ, Wilson JRU (2017) Quantifying errors and omissions in alien species lists: The introduction status of *Melaleuca* species in South Africa as a case study. NeoBiota 32: 89–105. https://doi.org/10.3897/neobiota.32.9842

Abstract

Introduced species lists provide essential background information for biological invasions research and management. The compilation of these lists is, however, prone to a variety of errors. We highlight the frequency and consequences of such errors using introduced *Melaleuca* (*sensu lato*, including *Callistemon*) species in South Africa as a case study. We examined 111 herbarium specimens from South Africa and noted the categories and sub-categories of errors that occurred in identification. We also used information from herbarium specimens and distribution data collected in the field to determine whether a species was introduced, naturalized and invasive. We found that 72% of the specimens were not named correctly. These were due to human error (70%) (misidentification, and improved identifications) and species identification problems (30%) (synonyms arising from inclusion of *Callistemon*, and unresolved taxonomy). At least 36 *Melaleuca* species have been introduced to South Africa, and field observations indicate that ten of these have naturalized, including five that are invasive. While most of the errors likely have negligible impact on management, we highlight one case where incorrect identification lead to an inappropriate management approach and some instances of errors in published lists. Invasive species lists need to be carefully reviewed to minimise errors, and herbarium specimens supported by DNA identification are required where identification using morphological features is particularly challenging.

Copyright *Llewellyn E.O. Jacobs et al.* This is an open access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Keywords
Biological invasions, *Callistemon*, herbarium specimen, invasive species listing, Myrtaceae, tree invasions

Introduction

Species lists form the basis for much of the current research on biological invasions (e.g. the Global Naturalized Alien Flora Database of van Kleunen et al. 2015). Such lists are also essential for guiding legislation, as input to decision making and risk assessment, and in the formulation of management policies and strategies (McGeoch et al. 2012; Latombe et al. 2016). Because resources required to address the threat of invasive species are limited, objective categorization of species is required to prioritize resource allocation according to species, areas and introduction pathways (McNeely et al. 2001, Nel et al. 2003, Wilson et al. 2013). Accurate lists of alien species, with data on their introduction status, are thus crucial resources, not just for the regions for which they are compiled, but also globally (Wilson et al. 2011). But, as with any information derived from a variety of sources, the compilation of lists is prone to a number of errors which can then be perpetuated in various ways (McGeoch et al. 2012). To address these concerns, it is thus essential that the error rates in species lists are assessed and ways to detect them are identified.

Pyšek et al. (2002) include alien taxa and their status in a flora of the Czech Republic. This well-compiled list lends itself to comparison with other regions and is an important example allowing for determinants and patterns of plant invasions at a global scale to be studied (Pyšek et al. 2004). Such lists are the essential building blocks on which assessments of the status of invasions in a country should be built (Latombe et al. 2016). By comparison, even though South Africa has a reasonably well-funded national programme for controlling invasive species, especially plants, research on lesser known invasive groups has only recently been given special attention (Wilson et al. 2013), and there is no comprehensive list of introduced and invasive species yet (Faulkner et al. 2015). A list of regulated invasive plant species was published in 2014 and this forms the basis for management plans and regulation (Department of Environmental Affairs 2014). However, this regulatory list is incomplete and contains several errors (per. obs.). Moreover, more species will need to be added as surveillance progresses, as more species demonstrate invasiveness, impacts are evaluated, and as errors in the list are discovered (Rouget et al. 2016).

For plants, herbaria are indispensable resources and reference sources for much botanical research which requires reliable species identifications, including the compilation of introduced species lists (Glen 2002). Funding for taxonomy and the upkeep of herbaria is declining worldwide (Smith et al. 2008, Guerin 2013, Pyšek et al. 2013) and is a concern that can be compounded because expertise for alien species is less likely to exist in any particular country. Herbarium specimens, upon which comprehensive lists are ideally based (Pyšek et al. 2013), require curation as taxa are revised or new information becomes available, e.g. from molecular and other studies

(e.g., Le Roux et al. 2010). Many alien taxa are underrepresented, remain unidentified for considerable periods of time, or are misidentified in herbaria (Pyšek et al. 2013). In this paper we explore the scale of this problem using taxa in the genus *Melaleuca* (*sensu* Craven (2006) and Brophy et al. (2013)) in South Africa as a case study.

The genus *Melaleuca* has not been distributed around the world as extensively as some other tree groups (e.g. *Eucalyptus,* a sister genus in the Myrtaceae) (Rejmánek and Richardson 2011). However, seven species are listed as invasive in the USA and South Africa (Rejmánek and Richardson 2013), including one of the world's poster-child plant invaders, *Melaleuca quinquenervia*, which has invaded large areas and caused major damage in the Everglades region in Florida (Richardson and Rejmánek 2011). The genus has about 290 species consisting of shrubs and trees, a number of which are planted in many parts of the world, largely as ornamentals, but also for timber, honey, bark and plant extracts (Brophy et al. 2013). Widespread cultivation of *Melaleuca* species is relatively recent, especially when compared to other genera in the Myrtaceae such as *Eucalyptus*, and records of naturalization and invasions in South Africa (Jacobs et al. 2014, 2015) and other parts of the world (Rejmánek and Richardson 2013) are comparably recent. Several species are recorded as weedy within Australia (Randall 2007), perhaps indicating that these (mostly) fire-adapted species could pose a risk to areas with similar fire-prone areas, such as the Cape Floristic Region of South Africa which has been invaded by many other woody plants from Australia (Wilson et al. 2014b).

In 2009, the discovery of several naturalised populations of *Melaleuca* species in South Africa prompted an evaluation of the introduction status for the entire group in the country (Wilson et al. 2013). Taxa such as *Melaleuca armillaris* subsp. *armillaris*, *M. viminalis* subsp. *viminalis* and *M. citrina* have been widely planted in South Africa and also warranted further study. This also provided an opportunity to reassess the accuracy of current published lists.

Here, we compile a list of *Melaleuca* species recorded as present in South Africa and determine the invasive status of each species. We use herbarium specimens to do this, while also noting the extent to which they are accurately identified and the types of errors which occur. We discuss consequences of errors and omissions and make recommendations on how these could be avoided and addressed.

Methods

Taxonomy

Generic limits in the tribe Melaleuceae have been the subject of much recent study (Brown et al. 2000, Wilson et al. 2005, Craven 2006, Edwards et al. 2010, Udovicic and Spencer 2012, Craven et al. 2014). We follow Craven (2006), Edwards et al. (2010) and Brophy et al. (2013) in adopting a broad concept of *Melaleuca*, i.e. including *Callistemon*. The further expansion of the genus *Melaleuca* to include *Beaufortia*, *Calothamnus*, *Conothamnus*, *Eremaea*, *Lamarchea*, *Petraeomyrtus*, *Phymatocarpus*, and *Regelia*

(Craven et al. 2014), has not yet been fully evaluated by the Australian taxonomic community, and these taxa are excluded from consideration for this study. Many *Melaleuca* species (especially those formerly recognised as *Callistemon*) are morphologically similar which makes them difficult to identify using morphological features. Several cultivars have been developed for some *Melaleuca* species in the *Callistemon* group and difficulty in identifying such specimens in South Africa is perhaps due to horticultural selection and the existence of hybrid and both sexual and apomictic species within the group (Craven 2009, Brophy et al. 2013).

Review of herbarium specimens and error classification

Herbarium specimens from the Compton herbarium (NBG) were examined to check whether specimen identifications were correct, and to provide accurate identifications where necessary. To do this, we used the taxonomic literature to compare morphological characters on the specimens with descriptions and taxonomic keys (in particular Craven and Lepschi 1999 and Brophy et al. 2013). Photographs and high-resolution scans of the specimens were taken for verification and future reference. Specimen identifications were checked against referenced herbarium specimens housed at the Australian National Herbarium (CANB; herbarium codes follow Thiers (2016)). The identifications of all specimens were subsequently confirmed by a taxonomic authority for *Melaleuca* (B.J. Lepschi).

Herbarium specimens were examined in 2013; any specimens accessioned or re-identified after this date were not included in the analysis. McGeoch et al. (2012) proposed an uncertainty classification that separates epistemic and linguistic errors into ten sub-categories. In this study we focussed on two of these sub-categories—human error and species identification. In keeping with terminology from McGeoch et al. (2012), we define the word "error" to be inclusive of actual and potential errors. For example, although a species name on a specimen was not currently accepted but no obvious mistake in listing arose from this yet, it was still recorded. As per McGeoch et al. (2012) scheme the human errors we discovered in this study were: misidentifications, and improved resolution of the identification (e.g. *Melaleuca* sp. identified as *M. parvistaminea*, or *M. armillaris* as *M. armillaris* subsp. *armillaris*). The only species identification error was unresolved taxonomy. A description of the different errors and how they were determined is shown in Table 1, as well as the frequency and relative proportions of the errors. Because the inclusion of *Callistemon* in an expanded *Melaleuca* is still under debate, synonyms where the genus name *Callistemon* changed to *Melaleuca* were placed under the species identification error type (instead of human error as per McGeoch et al. 2012 treatment). No synonyms outside of this situation were found and therefore synonyms relating to human error were absent from our dataset.

We also looked to see if there were any historical trends in the errors by comparing the years when taxa with particular errors were collected to the years when taxa with no errors were collected using Mann-Whitney U tests in R.

Table 1. Result of analysis of confirmed herbarium records (n=111), indicating the breakdown of correctly identified specimens with various error types. For full details see Suppl. material 1: Appendix. The errors identified here are error type 1 (i.e. human error, indicated as HE) and type 3 (i.e. species identification indicated as SI) as per McGeoch et al. (2012); synonyms are included in type 3 here (see Methods). The table only includes samples from the Compton Herbarium, Kirstenbosch (NBG).

Status	Description	Number of herbarium specimens	Examples
Correctly identified	The identification on the herbarium specimen was the same as determined by an expert in the group (the author: BL)	31	Seven specimens of *Melaleuca styphelioides* and five specimens of *M. hypericifolia* correctly identified
Misidentification (HE)	The identification on the herbarium specimen was to a currently accepted species, but not the correct one	31	*Melaleuca parvistaminea*, *M. armillaris* subsp. *armillaris* and *M. cuticularis* were misidentified as *M. ericifolia*
Further identification (HE)	The identification on the herbarium specimen could be refined, either by providing the specific epithet or the subspecific epithet	25	Several specimens (e.g. *M. rugulosa*) only identified to genus level; *M. armillaris* could be identified further to subspecies level
Unresolved taxonomy (SI)	The taxonomy used to identify the herbarium specimen was not resolved at that time, so any name provided will have some uncertainty around it.	2	Several names misapplied to *Melaleuca quinquenervia* (prior to 1968)
Synonym (SI)	The identification was confirmed, but the name on the herbarium specimen was not the most current accepted name	22	Nine specimens of *Callistemon rigidus* (a synonym of *C. linearis*, also a synonym of *Melaleuca linearis* var. *linearis*), *Callistemon viminalis* = *Melaleuca viminalis* subsp. *viminalis*

List compilation

Once correct identification for all specimens had been confirmed, we used these specimens as the source for compiling a list of species present in South Africa. We also used a list of cultivated plants based on herbarium records in southern Africa (Glen 2002), and a list of forestry trees and their uses in South Africa (Poynton 2009). The minimum residence time in South Africa was determined from the date on the oldest herbarium specimen for each species.

Naturalized populations were reported by a variety of conservation agencies, with the reports collated by the South African National Biodiversity Institute's Invasive Species Programme and through the Southern African Plant Invaders Atlas (Henderson et al. 2007; Wilson et al. 2013).

We collected height data as an estimate of age, presence/absence of reproductive structures and GPS coordinates for each plant. Using these data we were able to determine whether a species is sustaining itself, whether it is reproducing and/or spreading, hereby indicating the status of each species as introduced, naturalized or invasive according to the subcategories proposed by Blackburn et al. (2011).

Results

Review of herbarium specimens

A summary of the errors found is in Table 1 with details of each specimen that required a name change in Suppl. material 1: Appendix. Examples of the types of errors on are shown in Figure 1. Of the 111 specimens examined, only 31 specimens carried a currently accepted name (excluding current names for specimens that were incorrectly identified). Misidentifications made up the largest proportion of errors, while poorly resolved taxonomy was the reason for two specimens being incorrectly named. All synonyms required at least the genus name to be changed.

There was no significant effect of date of collection on whether an error was noted, or on particular errors types (dates of collection varied between 1907 and 2013).

List compilation

Our analysis of herbarium specimens and the lists in Glen (2002), also based on herbarium collections, is summarised in Table 2 (no additional species were found in Poynton's (2009) list), with species that did not have confirmed herbarium records discussed in Table 3. Thirty-six species are confirmed present in South Africa, of which ten species are naturalized – five of these are invasive (Fig. 2; Table 2). Five naturalized species were categorised as C3 according to Blackburn et al. (2011), indicating that individuals were surviving, reproducing and populations were self-sustaining, but less than 100 m from planting sites (Richardson et al. 2000; Wilson et al. 2014). *Melaleuca linearis* var. *linearis*, *M. hypericifolia*, *M. rugulosa* and *M. viminalis* subsp. *viminalis* are invasive, surviving and reproducing a significant distance from the site of original introduction, but not over a wide extent (D2). *Melaleuca parvistaminea* is invading several sites (E) near the towns of Tulbagh and Wolseley in the Western Cape province (Fig. 2c). There are a few separate invasive populations spread over ~10,000 ha, with a total of around 30 000 plants (Fig. 3; Jacobs et al. (2014)).

Discussion and conclusions

There are a number of ways that errors can be generated during the compilation of species lists (McGeoch et al. 2012), but here we show the challenges that exist at a fundamental stage of the listing process. Importantly, since only a subset of herbaria were analysed in detail, there could be additional errors (and in fact additional species) present in South Africa. The high proportion of misidentifications (Table 1) is concerning, indicating the difficulties encountered when dealing with novel species and highlighting the need for expertise on specific non-indigenous taxa. Synonymy, however, does not necessarily imply

Figure 1. Examples of the types of errors found on the herbarium specimens examined, **a** Misidentification: *Melaleuca salicina* misidentified as *Callistemon pallidus* **b** Improved identification: *Callistemon* sp. was further identified as *Melaleuca rugulosa* **c** Synonymy: *Callistemon rigidus* is a synonym of *C. linearis* but is currently accepted as *Melaleuca linearis* var. *linearis*, and **d** unresolved taxonomy: prior to 1968, *Melaleuca quinquenervia*, along with several other broad-leaved species were included under *M. leucadendra sensu lato*.

Table 2. List of 36 *Melaleuca* species in South Africa for which there is a confirmed herbarium record in either the Compton Herbarium, Kirstenbosch (NBG) or in the cultivated collection in the National Herbarium (PRE). Note that several other collections were searched, but no additional species could be discovered. Invasive status is according to Blackburn et al. (2011), with interpretation for trees from Wilson et al. (2014). All species were used as ornamentals although older records are often associated with historic forestry sites and arboreta. Later records were sourced mainly from gardens and nurseries. Recently used synonyms are listed and are intended to aid recognition of some species.

Species	Recently used synonym / misapplied name	Earliest record	Status in South Africa	Notes and references
Melaleuca alternifolia (Maiden & Betche) Cheel		1974	Introduced B2	
Melaleuca armillaris (Sol. ex Gaertn.) Sm. subsp. *armillaris*		1930	Naturalized C3	Widely cultivated ornamental. Potentially invasive.
Melaleuca brachyandra (Lindl.) Craven	*Callistemon brachyandrus* Lindl.	1968	Introduced B2	
Melaleuca bracteata F.Muell.		1981	Introduced B2	
Melaleuca citrina (Curtis) Dum.Cours.	*Callistemon citrinus* (Curtis) Skeels	1932	Naturalized C3	Bromilow (2010). Cultivars and hybrids also introduced. Cited in Rejmanek and Richardson (2013). Also recorded in Southern African Plant Invaders Atlas at Honingklip farm (3419AC) in 1998, but plants have been removed
Melaleuca cuticularis Labill.		1902	Introduced B2	
Melaleuca decora (Salisb.) Britten	*Melaleuca genistifolia* Sm.	1963	Introduced B2	
Melaleuca decussata R.Br.		1954	Introduced B2/B3	
Melaleuca diosmifolia Andrews		1933	Introduced B2	
Melaleuca elliptica Labill.		1963	Introduced B2	Observed in the deer park on the slopes of Devil's Peak, Table Mountain, Cape Town. Possibly naturalized, but no supporting evidence.
Melaleuca flammea Craven	*Callistemon acuminatus* Cheel	1986	Introduced B2	
Melaleuca fulgens R.Br.		1952	Introduced B2	
Melaleuca huegelii Endl. subsp. *huegelii*		1945	Introduced B2	
Melaleuca hypericifolia Sm.		1902	Invasive D2	Hickley et al. (2017). Field data at Hout Bay indicate spread > 100 m.
Melaleuca incana R.Br. subsp. *incana*		1967	Introduced B2	
Melaleuca incana subsp. *tenella* (Benth.) Barlow		1981	Introduced B2	
Melaleuca lanceolata Otto		1982	Introduced B2	

Species	Recently used synonym / misapplied name	Earliest record	Status in South Africa	Notes and references
Melaleuca lateritia A.Dietr.		1954	Introduced B2	
Melaleuca linariifolia Sm.		1958	Introduced B2	
Melaleuca linearis Schrad. & J.C.Wendl. var. *linearis*	*Callistemon linearis* (Schrad. & J.C.Wendl.) Colvill ex Sweet, *C. rigidus* R.Br.	1902	Invasive D2	Several plants found at Kluitjieskraal and 56 plants (30–130 cm height range) were found at two sites in Grahamstown.
Melaleuca nesophila F.Muell.		1967	Introduced B2	
Melaleuca nodosa Sm.		1961	Introduced B2	
Melaleuca pachyphylla (Cheel) Craven	*Callistemon pachyphyllus* Cheel	1983	Introduced B2	
Melaleuca paludicola Craven	*Callistemon sieberi* DC.	2011	Introduced B2	
Melaleuca parvistaminea Byrnes		1933	Invasive E	Invading a wetland system, Jacobs et al. (2014). Misidentified as the morphologically similar *M. ericifolia* Sm.
Melaleuca phoenicea (Lindl.) Craven	*Callistemon phoeniceus* Lindl.	1981	Introduced B2	
Melaleuca quinquenervia (Cav.) S.T.Blake	*Melaleuca leucadendra* L.	1928	Naturalized C3	Jacobs et al. (2015)
Melaleuca rhaphiophylla Schauer		1984	Introduced B2	
Melaleuca rugulosa (Schltdl. ex Link) Craven	*Callistemon rugulosus* (Schltdl. ex Link) DC.	1961	Invasive D1/D2	Devil's Peak, Cape Town. Spread > 500 m. ~20 adults. Seedlings growing in firebreak.
Melaleuca salicina Craven	*Callistemon salignus* (DC.) Colvill ex Sweet	1932	Naturalized C3	
Melaleuca squarrosa Donn ex Sm.		1994	Introduced B2	
Melaleuca styphelioides Sm.		1902	Naturalized C3	145 plants at Kluitjieskraal near the town Wosleley (60–450 cm height range)
Melaleuca subulata (Cheel) Craven	*Callistemon subulatus* Cheel	2013	Introduced B2/ Naturalized C3	Near water body 10km NE of Villiersdorp, possibly at Rockview dam near Grabouw
Melaleuca teretifolia Endl.		1967	Introduced B2	
Melaleuca thymifolia Sm.		1907	Introduced B2	
Melaleuca viminalis (Sol. ex Gaertn) Byrnes subsp. *viminalis*	*Callistemon viminalis* Sol. ex Gaertn subsp. *viminalis*	1948	Invasive D2	Widely planted with several localized sites of naturalization. Spreading along Kaaimans river ~3 km East of George

Figure 2. Examples of naturalized *Melaleuca* species in South Africa. **a** naturalized *M. quinquenervia* plants showing seed capsules opening after fire **b** *M. viminalis* subsp. *viminalis* naturalized along a stream in an urban setting **c** *Melaleuca parvistaminea* invading a conservation area that was previously under pine plantation, and **d** *M. linearis* var. *linearis* is invasive at another site previously under plantation with *M. parvistaminea* in background. Photos: **a, c** is E van Wyk, **b** is LEO Jacobs, **d** is DM Richardson.

human error, but rather that the use of an outdated or otherwise superseded taxonomy can lead to errors in interpretation, or incorrect estimates of numbers by subsequent users (McGeoch et al. 2012). In this study however, synonymy arose rather from differing perceptions of *Callistemon*, than from human error. Although the effect of synonymy is potentially large (McGeoch et al. 2012), the checking of synonymies is commonly practised. However, a rudimentary training in taxonomic principles is necessary for any practitioner dealing with scientific names. It is of concern that the inclusion of *Callistemon* in an expanded *Melaleuca* is still under debate. All synonym issues found in our study at least

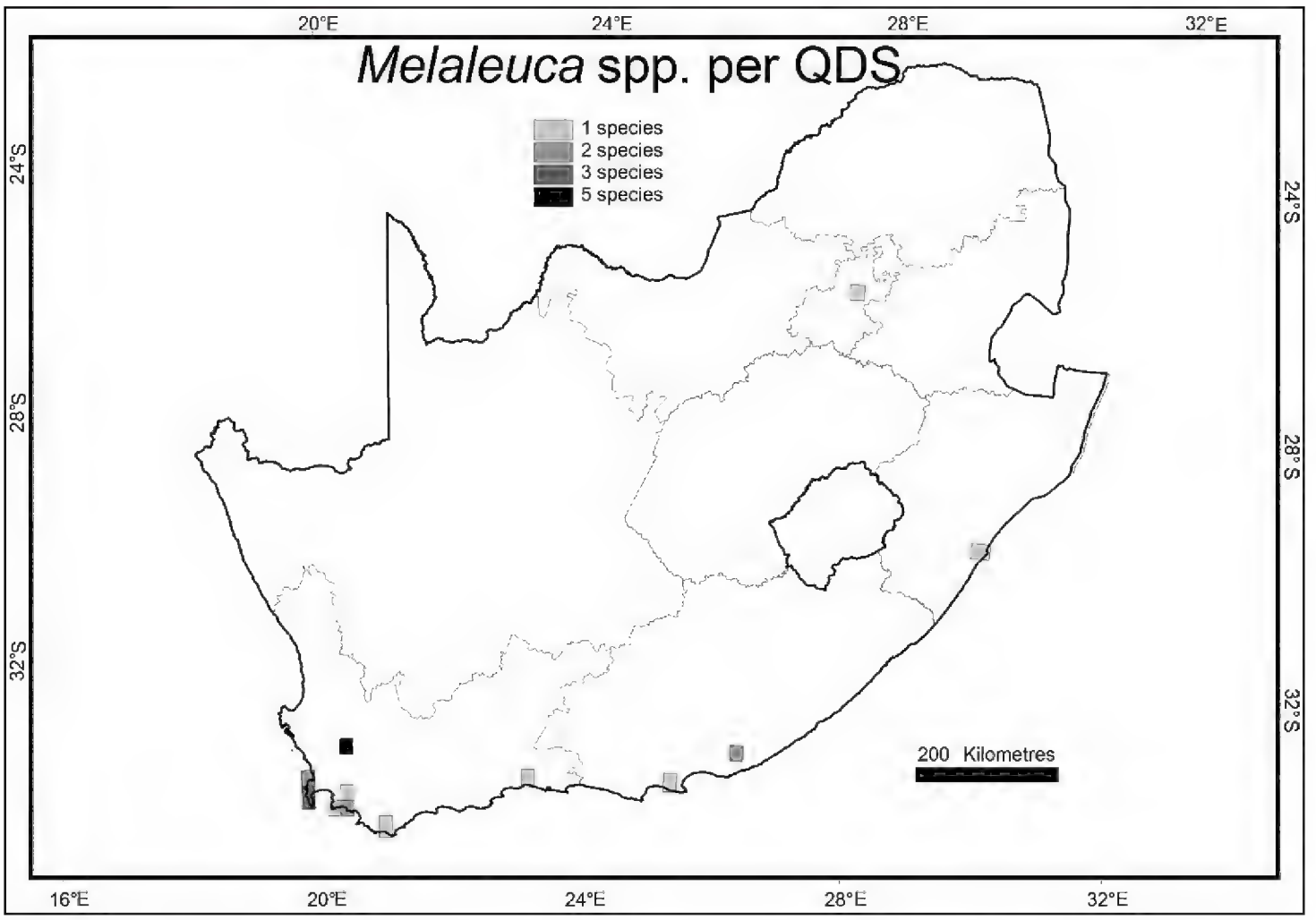

Figure 3. Localities of naturalized *Melaleuca* species in South Africa at the resolution of quarter-degree squares (QDS). Darker shading indicates a higher number of species. Grey borders are province boundaries.

Table 3. List of *Melaleuca* species recorded in South Africa for which there is no confirmed herbarium record.

Species	Earliest record	Source of information	Notes
Melaleuca hamulosa Turcz.	Unknown	Glen (2002)	No specimens found in PRE cultivated collection
Melaleuca glauca (Sweet) Craven [recorded as *Callistemon speciosus* (Sims) DC.]	Unknown	Glen (2002)	No specimens found in PRE cultivated collection
Melaleuca paludosa (Sweet) Craven [recorded as *Callistemon glaucus* (Bonpl.) Sweet]	1979	South African Plant Invaders Atlas (SAPIA)	Probably a misidentification. The only species found at the reported locality in Grahamstown is *M. linearis*.
Melaleuca pauperifolia F.Muell.	Unknown	Glen (2002)	No specimens found in PRE cultivated collection
Melaleuca wilsonii F.Muell.	1998	South African Plant Invaders Atlas (SAPIA, Australia's Virtual Herbarium (MEL 2053098A)	Land owner at Honingklip near Botrivier in the Western Cape reports historic occurrence of "bottlebrushes" but no *Melaleuca* species occur at this site as of 2011.
Melaleuca nervosa (Lindl.) Cheel	Unknown	Gibbs (1998)	One tree recorded at Damara Farm near Malmesbury. Several *Acacia* species trials were also carried out at this site

required the genus name to be updated. Lists not taking this into account could generate errors of a greater magnitude than errors relating only to the specific epithet.

Lists therefore require the application of taxonomic expertise on taxa not native to a particular region (Pyšek et al. 2013). The knowledge generated from these lists form the basis for informing end users, (e.g. quarantine officials, conservation agencies) that perform crucial functions in stemming the tide of biological invasions and informing future research (e.g. identifying biological control agents) requiring accurate species identifications. Herbaria have often served as barometers for new and rediscovered alien plant species. They also provide a reference source for research or conservation initiatives that require accurate species names. The ongoing decline of resources being allocated to the maintenance of herbaria worldwide will adversely affect many research fields including invasion biology (Guerin 2013, Pyšek et al. 2013). We strongly believe that part of the funding for invasive species management needs to be allocated to the maintenance and functioning of herbaria and other collections as they are an essential resource for the work (this has begun to be supported in South Africa but further sustained resources need to be devoted to this). The same could be suggested for other fields of botanical research.

While genetic verification of species identifications is proving to be a reliable means of verifying a species, classical taxonomy still remains crucial to the identification of new species to a region (Pyšek et al. 2013). In the absence of molecular data suitable for use in species identification, identifications based on morphology are usually adequate (Pyšek et al. 2013). For these reasons, and an uncertain taxonomy in some cases, we found morphological identification based on published descriptions and keys the best approach to reviewing herbarium specimens of *Melaleuca*. Because suitable molecular data is often lacking, we recommend that DNA barcoding efforts should prioritise potentially invasive genera, so that species can be accurately identified in regions where expertise on that group is likely absent. Species identification issues due to uncertain or unresolved taxonomy can be avoided by continued taxonomic research (Edwards et al. 2010). This research will likely be conducted in the country of origin and therefore cross-border communication and collaboration between taxonomists are essential (Smith et al. 2008, Pyšek et al. 2013). Errors could be avoided by either collaborating with researchers from regions where alien species are native, thus tying into a strategic response of the *Global Invasive Alien Species Strategy* (McNeely 2001) or by investing in local taxonomic expertise on key alien groups. There are several ways in which these groups could be identified based on known patterns of invasion. Minimum residence time, invasiveness in other regions and weedy species are data obtainable from herbarium specimens and could thus be used to identify these groups.

Identification errors noted in this study have had direct implications. *Melaleuca parvistaminea* was initially misidentified in 2011 as the morphologically similar *M. ericifolia*. *Melaleuca parvistaminea* was only formally described in 1984 and collections prior to this were treated within the broad concept for *M. ericifolia*. Some *M. armillaris* subsp. *armillaris* specimens were also misidentified as *M. ericifolia* (e.g. NBG0269364). *Melaleuca ericifolia* is regarded as being predominantly clonal rather than reseeding. This affected management actions, through unforeseen profuse recruitment via seed

after clearing and the absence of clonal spread and resprouting (Jacobs et al. 2014). The incorrect name was perpetuated into Richardson and Rejmánek's (2011) global list of invasive trees and shrubs, but corrected in an update of this list (Rejmánek and Richardson 2013). Although this was not investigated, it is possible that publications citing *Melaleuca* species from Richardson and Rejmánek (2011) could carry this mistake forward.

Effective pre-emptive control efforts rely heavily on whether alien species are listed as invasive in that region or are known to be invasive elsewhere (Mack 1996). As a result of debate surrounding generic limits in the tribe Melaleuceae, especially regarding the recognition of *Callistemon* as a segregate genus (Craven 2006; Udovicic and Spencer 2012, Edwards et al. 2010, Craven et al. 2014), species lists included in the recently published *Alien and Invasive Species Regulations in South Africa* (DEA 2014) may generate errors due to synonymy issues. For example, the regulations list *Callistemon rigidus*, which is now treated as a synonym of *C. linearis* if one accepts the separation of the two genera (see Council of Heads of Australasian Herbaria 2016); if a broad concept of *Melaleuca* is adopted, then the taxon should be listed as *Melaleuca linearis*. Moreover, several species have been omitted from the regulations, e.g. *Melaleuca parvistaminea,* a species which is clearly invasive and poses a considerable environmental threat (Jacobs et al. 2014). Recognition of situations like these requires adequate taxonomic expertise and familiarity with the group in question.

Hybridization and horticultural selection for some *Melaleuca* species, especially those in the *Callistemon* group can further complicate accurate identification (Brophy et al. 2013). Hybrids and several cultivars exist for some taxa and it is not clear whether some hybrids or cultivars are more invasive than others. Moreover, some *Melaleuca* species, such as *M. linearis*, are apomictic and may further contribute to species identification problems.

We identified ten species of *Melaleuca* naturalised in the Western Cape province of South Africa, but invasions of taxa in this genus are at an early stage, and there is likely to be a high level of invasion debt (*sensu* Rouget et al. 2016). Unlike other invasive Australian tree and shrub species (e.g. *Acacia* and *Eucalyptus*), *Melaleuca* species were never widely disseminated in South Africa for forestry or dune stabilisation. *Melaleuca quinquenervia* was introduced and widely disseminated for a variety of reasons, including ecosystem engineering, in the USA (Dray et al. 2006). No wide scale plantings took place in South Africa. *Melaleuca* introductions and plantings in South Africa have been for ornamental purposes, mostly in the last few decades. Because naturalized populations are still small there is still the opportunity to eradicate several species if action is taken quickly and with sufficient resources. Besides the small populations, other factors that suggest that eradication is feasible are the short-lived serotinous seed banks, the effectiveness of available herbicides (Jacobs et al. 2014, van Wyk and Jacobs 2015), limited dispersal capability (inferred from Rejmánek and Richardson 2011) and a focused, national programme with a mandate to respond to incursions (Wilson et al. 2013). The high level of errors in identification which we found in this study, however, highlights the urgent need to assess and improve the accuracy of alien species lists.

Acknowledgements

We acknowledge financial support from the DST-NRF Centre of Excellence for Invasion Biology (C•I•B), Cape Nature, the South African National Department of Environment Affairs (DEA) through its funding of the South African National Biodiversity Institute's Invasive Species Programme and through the collaborative research project "Integrated management of invasive alien species in South Africa" of the C•I•B and the DEA, and the National Research Foundation (grant 85417 to DMR). We are grateful to the many herbarium staff for their kind assistance, to Riki de Villiers for support with maps and to Pieter Winter for valuable comments on this manuscript.

References

Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, Jarošík V, Wilson JRU, Richardson DM (2011) A proposed unified framework for biological invasions. Trends in Ecology and Evolution 26: 333–339. doi: 10.1016/j.tree.2011.03.023

Bromilow C (2010) Problem plants and alien weeds of South Africa. Briza (Arcadia): 1–424.

Brophy JJ, Craven LA, Doran JC (2013) Melaleucas: their botany, essential oils and uses. ACIAR Monograph No. 156. Australian Centre for International Agricultural Research, Canberra, 1–415.

Brown GK, Udovicic F, Ladiges PY (2001) Molecular phylogeny and biogeography of *Melaleuca*, *Callistemon* and related genera (Myrtaceae). Australian Systematic Botany 14: 565–585. doi: 10.1071/SB00029

Council of Heads of Australasian Herbaria (2016) Australian Plant Census. http://www.anbg.gov.au/chah/apc/

Craven LA (2006) New combinations in *Melaleuca* for Australian species of *Callistemon* (Myrtaceae). Novon 16: 468–475. doi: 10.3417/1055-3177(2006)16[468:NCIMFA]2.0.CO;2

Craven LA, Lepschi BJ (1999) Enumeration of the species and infraspecific taxa of *Melaleuca* (Myrtaceae) occurring in Australia and Tasmania. Australian Systematic Botany 12: 819–927. doi: 10.1071/SB98019

Craven LA, Edwards RD, Cowley KJ (2014) New combinations and names in *Melaleuca*. Taxon 63: 663–670. doi: 10.12705/633.38

Craven LA (2009) *Melaleuca* (Myrtaceae) from Australia. Novon 19: 444–453. doi: 10.3417/2007137

Department of Environmental Affairs (2014) National Environmental Management: Biodiversity Act 2004 (Act No. 10 of 2004) Alien and Invasive Species Regulations. DEA Government Gazette 2014: 3–32.

Dray FA, Bennet BC, Center TD (2006) Invasion history of *Melaleuca quinquenervia* (Cav.) ST Blake in Florida. Castanea 71: 210–225. doi: 10.2179/05-27.1

Edwards RD, Craven LA, Crisp MD, Cook LG (2010) *Melaleuca* revisited: cpDNA and morphological data confirm that *Melaleuca* L. (Myrtaceae) is not monophyletic. Taxon 59: 744–754.

Faulkner KT, Spear D, Robertson MP, Rouget M, Wilson JRU (2015) An assessment of the information content of South African alien species databases. Bothalia: African Biodiversity and Conservation 45: 11 pp. [Art. #1103]

Glen HF (2002) Cultivated Plants in Southern Africa: Names, Common Names and Literature. Jacana Media, Johannesburg, 428 pp.

Guerin GR (2013) The value of herbaria to diverse collections-based research. Australasian Systematic Botany Society Newsletter 157: 43–44.

Henderson L (2007) Invasive, naturalized and casual alien plants in southern Africa: a summary based on the Southern African Plant Invaders Atlas (SAPIA). Bothalia 37: 215–248. doi: 10.4102/abc.v37i2.322

Hickley KI, Kaplan H, Van Wyk, E, Renteria JL, Boatwright JS (2017) Invasive potential and management of *Melaleuca hypericifolia* (Myrtaceae) in South Africa. South African Journal of Botany 108: 110–116. doi: 10.1016/j.sajb.2016.10.007

Jacobs LEO, Richardson DM, Wilson JRU (2014) *Melaleuca parvistaminea* Byrnes (Myrtaceae) in South Africa: Invasion risk and feasibility of eradication. South African Journal of Botany 94: 24–32. doi: 10.1016/j.sajb.2014.05.002

Jacobs LEO, van Wyk E, Wilson JRU (2015) Recent discovery of small naturalised populations of Melaleuca quinquenervia (Cav.) S.T. Blake in South Africa. BioInvasions Records 4: 53–59. doi: 10.3391/bir.2015.4.1.09

Latombe G, Pyšek P, Jeschke JM, Blackburn TM, Bacher S, Capinha C, Costello MJ, Fernández M, Gregory RD, Hobern D, Hui C, Jetz W, Kumschick S, McGrannachan C, Pergl J, Roy HE, Scalera R, Squires ZE, Wilson JRU, Winter M, Genovesi P, McGeoch MA (2016) A vision for global monitoring of biological invasions. Biological Conservation (in press). doi: 10.1016/j.biocon.2016.06.013

Le Roux JJ, Geerts S, Ivey P, Krauss S, Richardson DM, Suda J, Wilson JRU (2010) Molecular systematics and ecology of invasive Kangaroo Paws in South Africa: management implications for a horticulturally important genus. Biological Invasions 12: 3989–4002. doi: 10.1007/s10530-010-9818-4

Mack RN (1996) Predicting the identity and fate of plant invaders: emergent and emerging approaches. Biological Conservation 78: 107–121. doi: 10.1016/0006-3207(96)00021-3

McGeoch MA, Spear D, Kleynhans EJ, Marais E (2012) Uncertainty in invasive alien species listing. Ecological Applications 22: 959–971. doi: 10.1890/11-1252.1

McNeely JA, Mooney HA, Neville LE, Schei P, Waage JK (Eds) (2001) A Global Strategy on Invasive Alien Species. IUCN, Gland, 50 pp.

Nel JL, Richardson DM, Rouget M, Mgidi T, Mdzeke N, Le Maitre DC, van Wilgen BW, Schonegevel L, Henderson L, Neser S (2004) A proposed classification of invasive alien plant species in South Africa: towards prioritising species and areas for management action. South African Journal of Science 100: 53–64.

Poynton RJ (2009) Tree planting in southern Africa: vol. 3 other genera. Department of Agriculture, Forestry, and Fisheries, (Pretoria, South Africa)

Pyšek P, Sádlo J. Mandák B (2002) Catalogue of alien plants of the Czech Republic. Preslia 74: 97–186.

Pyšek P, Richardson DM, Rejmánek M, Webster GL, Williamson M, Kirschner J (2004) Alien plants in checklists and floras: towards better communication between taxonomists and ecologists. Taxon 53: 131–143. doi: 10.2307/4135498

Pyšek P, Hulme PE, Meyerson LA, Smith GF, Boatwright JS, Crouch NR, Figueiredo E, Foxcroft LC, Jarošík V, Richardson DM, Suda J, Wilson JRU (2013) Hitting the right target: taxonomic challenges for, and of, plant invasions. AoB Plants 5: plt042. doi: 10.1093/aobpla/plt1042

Randall RP (2007) A global compendium of weeds. http://www.hear.org/gcw/

Rejmánek M, Richardson DM (2011) Eucalypts. In: Simberloff D, Rejmánek M (Eds) Encyclopedia of biological invasions. University of California Press, Berkeley, 203–209.

Rejmánek M, Richardson DM (2013) Trees and shrubs as invasive alien species – 2013 update of the global database. Diversity and Distributions 19: 1093–1094. doi: 10.1111/ddi.12075

Richardson DM, Pyšek P, Rejmánek M, Barbour MG, Panetta FD, West CJ (2000) Naturalization and invasion of alien plants: concepts and definitions. Diversity and Distributions 6: 93–107. doi: 10.1046/j.1472-4642.2000.00083.x

Richardson DM, Rejmánek M (2011) Trees and shrubs as invasive alien species – a global review. Diversity and Distributions 17: 788–809. doi: 10.1111/j.1472-4642.2011.00782.x

Rouget M, Robertson MP, Wilson, JRU, Hui C, Essl F, Rentería JL, Richardson DM (2016) Invasion debt – quantifying future biological invasions. Diversity and Distributions 22: 445–456. doi: 10.1111/ddi.12408

Smith RD, Aradottir GI, Taylor A, Lyal C (2008) Invasive species management: what taxonomic support is needed? Global Invasive Species Programme, Nairobi, 1–44.

Thiers B. Index Herbariorum: A global directory of public herbaria and associated staff. New York Botanical Garden's Virtual Herbarium. http://sweetgum.nybg.org/science/ih/

Udovicic F, Spencer RD (2012) New combinations in *Callistemon* (Myrtaceae). Muelleria 30: 23–25.

van Kleunen M, Dawson W, Essl F, Pergl J, Winter M, Weber E, Kreft H, Weigelt P, Kartesz J, Nishino M, Antonova LA, Barcelona JF, Cabezas FJ, Cardenas D, Cardenas-Toro J, Castano N, Chacon E, Chatelain C, Ebel AL, Figueiredo E, Fuentes N, Groom QJ, Henderson L, Inderjit, Kupriyanov A, Masciadri S, Meerman J, Morozova O, Moser D, Nickrent DL, Patzelt A, Pelser PB, Baptiste MP, Poopath M, Schulze M, Seebens H, Shu W-s, Thomas J, Velayos M, Wieringa JJ, Pyšek P (2015) Global exchange and accumulation of non-native plants. Nature 525: 100–103. doi: 10.1038/nature14910

van Wyk E, Jacobs LEO (2015) Prospects for extirpating small populations of the wetland invader *Melaleuca quinquenervia* from South Africa: a case study from the Western Cape region. African Journal of Aquatic Science 40: 299–306. doi: 10.2989/16085914.2015.1076374

Wilson JRU, Gairifo C, Gibson MR, Arianoutsou M, Bakar BB, Baret S, Celesti-Grapow L, DiTomaso JM, Dufour-Dror J-M, Kueffer C, Kull CA, Hoffmann JH, Impson FAC, Loope LL, Marchante E, Marchante H, Moore JL, Murphy DJ, Tassin J, Witt A, Zenni RD, Richardson DM (2011) Risk assessment, eradication, and biological control: global efforts to limit Australian acacia invasions. Diversity and Distributions 17: 1030–1046. doi: 10.1111/j.1472-4642.2011.00815.x

Wilson JRU, Ivey P, Manyama P, Nänni I (2013) A new national unit for invasive species detection, assessment and eradication planning. South African Journal of Science 109(5/6): 1–13. doi: 10.1590/sajs.2013/20120111

Wilson JRU, Caplat P, Dickie I, Hui C, Maxwell BD, Nuñez MA, Pauchard A, Rejmánek M, Richardson DM, Robertson MP, Spear D, Webber BL, van Wilgen BW, Zenni RD (2014a) A standardized set of metrics to assess and monitor tree invasions. Biological Invasions 16: 535–551. doi: 10.1007/s10530-013-0605-x

Wilson JRU, Gaertner M, Griffiths CL, Kotzé I, Maitre DC, Marr SM, Picker M, Spear D, Stafford L, Richardson DM, van Wilgen BW, Wannenburgh A (2014b) Biological invasions in the Cape Floristic Region: history, current patterns, impacts, and management challenges. In: Allsopp N, Colville J, Verboom T (Eds) Fynbos: ecology, evolution, and conservation of a megadiverse region. Oxford University Press, Oxford, 274–298. doi: 10.1093/acprof:oso/9780199679584.003.0012

Wilson PG, O'Brien MM, Heslewood MM, Quinn CJ (2005) Relationships within Myrtaceae *sensu lato* based on a matK phylogeny. Plant Systematics and Evolution 251: 3–19. doi: 10.1007/s00606-004-0162-y

Supplementary material 1

Appendix and Supplementary Figures

Authors: Llewellyn E.O. Jacobs, David M. Richardson, Brendan J. Lepschi, John R.U. Wilson

Data type: Table (Appendix 1), map (supplementary figures)

Explanation note:

Appendix: Herbarium specimens requiring name changes, indicating accession numbers, original species name, corrected species name and types of errors.

Supplementary Figures: Distribution at the quarter-degree cell scale of nine *Melaleuca* species naturalized in South Africa. No map is given for *Melaleuca citrina* because historic sites of naturalization could not be confirmed or plants were no longer there.

Copyright notice: This dataset is made available under the Open Database License (http://opendatacommons.org/licenses/odbl/1.0/). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.